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The BeppoSAX last score in Gamma-Ray Burst astrophysics: the $E_{p,i}$ – E_{iso} relationship

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Abstract. The Italian–Dutch X–ray mission BeppoSAX had a great impact in the field of Gamma-Ray Burst (GRB) astrophysics, in particular with the the discovery of afterglow emission, leading ultimately to the determination of GRB distance scale and energetics, the discovery of new classes of events like dark GRBs, X–ray rich GRBs and X–Ray Flashes (XRF), the first direct evidence of the GRB/SN connection. Here we review the observations and implications of the relationship between the photon energy, $E_{p,i}$, at which the intrinsic (i.e. corrected for cosmological redshift) EF(E) spectrum peaks and the isotropic equivalent radiated energy, E_{iso}, discovered by Amati et al.(2002) based on BeppoSAX measurements when the mission was close to the end of its operation. This relation, subsequently confirmed and extended to the X–ray richest GRBs by HETE–2 measurements, can be used to discriminate among the various scenarios for the prompt emission of GRBs, is a challenging test for jet models and the understanding of the GRB/SN connection and can be also used to build up redshift estimators.

Key words. X–rays: observations – Gamma–rays: observations – Gamma–rays: bursts

1. The BeppoSAX revolution in GRB astrophysics

The observations of Gamma–Ray Bursts (GRB) performed by the Italian–Dutch satellite BeppoSAX (Boella et al. 1997) from April 1996 to April 2002 had an unprecedented impact in the field. Indeed, despite the major contribution given by the NASA CGRO/BATSE experiment during the '90s, which allowed e.g. a deep study of the complexity and variety of the light curves, the discovery of a bi–modal distribution of the durations (short GRBs, with durations < 1–2 s, and long GRBs, with durations from few seconds up to hundreds of seconds), the empirical description of their non thermal spectra and the study of the distributions of the spectral parameters, the evidence of isotropic distribution of GRBs directions in the sky and of inhomogeneous distribution of their intensities, before BeppoSAX the knowledge of GRBs distance scale, and thus energetics, was still missing, preventing challenging tests of emission mechanisms and, in particular, the comprehension of the nature of the progenitors.

The BeppoSAX payload included a set of Narrow Field instruments (NFI), covering the energy band 0.1–300 keV with fields of view

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of 0.5–1.3°, and two wide field instruments, the Wide Field Cameras (WFC, 2–28 keV, FOV 20×20° FWHM, angular resolution of 3') and the Gamma–Ray Burst Monitor (GRBM, 40–700 keV, open FOV). This payload configuration, together with the enthusiastic and efficient mission support, resulted to be extremely powerful for GRB studies. Indeed, the co–alignment of the two WFC with two of the four units of the GRBM made it possible to detect GRBs in both instruments at a rate of ∼1 event/month. The X–ray emission, much weaker than the hard X–ray / soft gamma–ray emission, of these events could be identified in the WFC light curves thanks to the trigger given by the GRBM. The exploitation of the WFC spatial resolution allowed the localization of these GRB sources with an unprecedented accuracy of few arcmin. After the first of such detections, GRB960720, discovered during off–line analysis, the BeppoSAX GRB team activated an on–line procedure at the Science Operation Center (SOC) for the quick localization of GRBs simultaneously detected by the WFC and GRBM and their follow–up within few hours (6–12 on the average) with the NFI. This led to the discovery of the X–ray afterglow emission of GRBs and, thanks to the further refined localizations provided by the NFI, to the discovery of optical, IR, radio counterparts. In addition to unveiling a new phenomenology (afterglow emission) and opening new observational windows (optical, IR, radio), the major consequence of these discoveries was the possibility of setting the (cosmological, up to z = 4.5) distance scale, and consequently the (huge, up to $\sim10^{54}$ ergs assuming isotropic emission) energetics, thanks to redshift determinations by means of spectroscopy of optical counterparts and/or host galaxies.

BeppoSAX provided also other crucial results, which contributed to the huge step forward toward the comprehension of GRBs performed in the last years: extensive studies of spectral and temporal properties of the prompt emission from several hundreds of keV down to ∼2 keV (the low energy threshold of the WFC), characterization of the temporal decay and spectral properties of X–ray afterglows, discovery of absorption features in the prompt emission spectra of few GRBs, discovery of emission lines in the afterglow spectra of few GRBs, discovery of X–ray rich GRBs, discovery of X–Ray Flashes (XRF, GRBs showing typical emission in the WFC but no emission in the GRBM 40–700 keV energy band), first direct evidence of the GRB/SN connection (GRB980425/SN1998bw), evidence of an achromatic break in the decay light curve of some GRBs (in several cases commonly interpreted as due to jetted emission). For a review, see Amati (2004a) and references therein.

Toward and after the end of BeppoSAX operation, new missions continued its studies: Chandra and XMM–Newton, for the study of X–ray afterglows, and mainly HETE–2 (NASA GRB dedicated mission, 1–400 keV) for soft to hard X–ray study of the prompt emission and arcmin localization, provided in the very last years also by INTEGRAL at a rate of about 1 event per month, and, with less accuracy, by the InterPlanetary Network (IPN). In particular, HETE–2 extended the study of X–ray rich GRBs and XRFs and provided the detection of the second GRB with clear evidence of association with a SN, GRB030329.

2. Spectra and energetics of the prompt emission of GRBs

GRBs are characterized by non thermal spectra showing in many cases substantial evolution. Most average and time resolved spectra can be modeled with the Band function (a smoothly broken power–law) introduced to describe the BATSE (25-2000 keV) data, whose parameters are the low energy spectral index, α, the high energy spectral index, β, the break energy, E_0, and the overall normalization. The photon energy at which the EF(E) spectrum peaks is given by $E_p = E_0 \times (2 + \alpha)$. The non thermal nature of GRB spectra is at the basis of the standard scenario for their emission, in which the kinetic energy of an ultra-relativistic fireball (a plasma made of pairs, photons and a small quantity of baryons) is dissipated into electromagnetic radiation by means of synchrotron emission originated in internal shocks between colliding shells and/or the external shock of the fireball with the ISM. Indeed, the spectral shape of most GRBs can be satisfactorily reproduced by Synchrotron Shock Models (SSM). Nevertheless, the time resolved analysis of bright BATSE GRBs showed that during the initial phase of the emission of several events the low energy index is inconsistent with the prediction of SSM, i.e. α is found to be higher than the synchrotron limit of −0.67. This evidence has been explained by invoking e.g. the presence of an additional X–ray component due to Compton up–scattering of UV photons surrounding the GRB source by the ultra relativistic electrons of the fireball, the presence of a thermal component emitted by the photosphere of the fireball, a particular distribution of the pitch angles of electrons radiating via synchrotron emission. Other relevant outcomes of the analysis of BATSE events were the evidences of a substantial clustering of E_p values around 200 keV, a positive correlation between GRB intensity and spectral hardness and a negative correlation between GRB duration and spectral hardness. In the recent years, the discovery and study of X–ray rich events and XRFs, due to the extension to the X–ray energy band of the search and spectral analysis of GRBs allowed by BeppoSAX and HETE–2, showed that the distribution of E_p is much less clustered than inferred basing on BATSE data and, in particular, that it is characterized by a low energy tail extending at least down to ∼1 keV (Barraud et al. 2003).

Since the BeppoSAX breakthrough discoveries in 1997, more than 30 redshift estimates have been performed, all pertaining long duration GRBs. As a consequence, for these events it is possible to compute the peak luminosity, the average luminosity and the total radiated energy by exploiting the distance estimate and the measured peak flux and fluence. In the simplest assumption of isotropic emission, the radiated energy, E_{iso}, ranges from $\sim10^{51}$ erg to $\sim10^{54}$ erg for most GRBs and extends down to $\sim10^{49}$ erg when including XRFs, see e.g. Lamb, Donaghy & Graziani (2004). The highest energies are very difficult to explain even for the most popular models fro the progenitors of bright–long GRBs, the hypernova–collapsar models, especially when taking into account the very low efficiency in converting the kinetic energy of the fireball into electromagnetic radiated energy. This difficulty is, at least partially, overcome by assuming that the GRB emission is collimated. Indeed, the achromatic breaks observed in the afterglow decay curves of several GRBs can be interpreted in the light of simple uniform jet models. In these scenarios, a break is expected when, because of the deceleration of the fireball, the relativistic beaming angle exceeds the jet opening angle, which can be derived from the break time by making assumptions on the properties of the fireball (e.g. the Lorentz factor) and the circum–burst environment (e..g density). Basing on the achromatic breaks in the decay light curves of the afterglows of GRBs with known redshift, the distribution of the total radiated energies in the jet hypothesis, E_{jet}, is found to be clustered around $\sim10^{51}$ erg, see e.g. Bloom, Frail & Kulkarni (2003).

3. Discovery and confirmation of the $E_{p,i}$ – E_{iso} relationship

In 2002, Amati et al. presented the results of the analysis of the average WFC (2–28 keV) and GRBM (40–700 keV) spectra of 12 BeppoSAX GRBs with known redshift (9 firm measurements and 3 possible values). By fitting the redshift–corrected spectra with the Band function, they were able to estimate the intrinsic (i.e. in the source cosmological rest frame) values of the spectral parameters. Also, by integrating the best fit model of the intrinsic time integrated spectrum and adopting a standard cosmology, they computed the total radiated energy in the 1–10000 keV band assuming isotropic emission, E_{iso}, and performed correlations studies between intrinsic spectral parameters, E_{iso} and the redshift z . Thanks to the extension of the analysis down to X–rays, the truncation effects in the determination of spectral parameters, in particular of the low energy index α and of the intrinsic peak energy $E_{p,i}$, were substantially reduced with respect to previous analysis based e.g. on BATSE data. In addition, all the GRBs in the sample had peak fluxes and fluences well above the detection

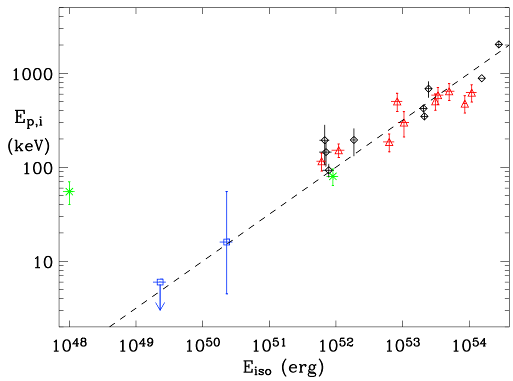

Fig. 1. $E_{p,i}$ and E_{iso} values for the 9 GRBs with firm redshift estimates included in the sample by (Amati et al. 2002, rombs), the 10 more events included in the sample of (Amati 2004b, triangles), the two XRFs (XRF020903 and XRF030723) included in the sample of (Lamb, Donaghy & Graziani 2004, squares) and the two GRBs with most firmly associated with a SN event (GRB980425, GRB030329; asterisks). The dashed line is the law $E_{p,i} = 100 \times E_{iso}^{0.5}$ ($E_{p,i}$ in units of keV and E_{iso} in units of 10^{52} erg).

threshold.
The more relevant outcomes of this work were an indication of a positive trend between E_{iso} and z and, in particular, the evidence of a strong correlation between $E_{p,i}$ and E_{iso} . The correlation coefficient between $\log(E_{p,i})$ and $\log(E_{iso})$ was found to be 0.949 for the 9 GRBs with firm redshift estimates, corresponding to a chance probability of 0.005%. The slope of the power–law best describing the trend of $E_{p,i}$ as a function of E_{iso} was ~0.5 . This work was extended by Amati (2004b) by including in the sample 10 more events with known redshift (3 new BeppoSAX GRBs, 4 HETE–2 GRBs, 3 BATSE GRBs) for which new spectral data (BeppoSAX events) or published best fit spectral parameters (BATSE and HETE–2 events) were available. The $E_{p,i} - E_{iso}$ relationship was confirmed and its significance increased, giving a correlation coefficient similar to that derived by Amati et al. (2002) but with a much higher number of events. Basing on HETE–2 measurements, Lamb, Donaghy & Graziani (2004) not only confirm the $E_{p,i} - E_{iso}$ relationship but remarkably extend it to XRFs, showing that it holds over three order of magnitudes in $E_{p,i}$ and five order of magnitudes in E_{iso} . In Fig. 1 we show $E_{p,i}$ as a function of E_{iso} for the events included in the sample of Amati (2004b), the two XRFs (XRF020903 and XRF030723) in the sample of Lamb, Donaghy & Graziani (2004) and the two GRBs for which there is the most firm evidence of association with a SN event, GRB980425 and GRB030329. In addition to the correlation extending from XRFs up to the most energetic GRBs, it can be seen that the values of GRB980425 / SN1998bw are completely inconsistent with the relationship. As shown e.g. by Lamb, Donaghy & Graziani (2004), the Amati et al. (2002) relationship holds also when substituting E_{iso} with the average isotopic equivalent luminosity L_{iso} . In particular, the slope of this relation is consistent with that of the $E_{p,i} - E_{iso}$ relation. Liang, Dai & Wu (2004), basing on the spectral analysis of BATSE bright GRBs with unknown redshift and assuming a GRB redshift distribution derived from star formation rate models, infer that the $E_{p,i} - L_{iso}$ relationship holds also within GRBs. Finally, very recently Ghirlanda, Ghisellini & Lazzati (2004) found a correlation between $E_{p,i}$ and the total radiated energy in the assumption of collimated emission, E_{jet} .

4. Implications of the $E_{p,i} - E_{iso}$ relationship

The discovery of the $E_{p,i} - E_{iso}$ relationship confirms and explains observational evidences found before the BeppoSAX era, when redshift estimates were not available, like e.g. the hardness–intensity correlation. Moreover, basing on the spectral analysis of BATSE data Lloyd, Petrosian & Mallozzi (2000) inferred the existence of a power–law correlation between $E_{p,i}$ and E_{iso}, with a slope in the range 0.4–0.7, consistent with the value of ~0.5 found by Amati et al. (2002).
The $E_{p,i} - E_{iso}$ relationship, with its extension over several orders of magnitude both in $E_{p,i}$

and E_{iso} has a strong impact both for the mechanisms and the geometry of the emission of GRBs. The physics of the prompt emission is still far to be settled and a variety of scenarios, within the standard fireball picture, have been proposed, e.g. SSM internal shocks, Inverse Compton (IC) dominated internal shocks, external shocks, innermost models, occurring in a kinetic energy dominated fireball or a Poynting flux dominated fireball. See Zhang & Meszáros (2002) for a review. In general, both $E_{p,i}$ and E_{iso} depend on the fireball bulk Lorentz factor, Γ, in a way that varies in each scenario. Thus, the existence of a correlation between $E_{p,i}$ and E_{iso} is predicted in nearly all scenarios, but the fact that it is positive and has a slope of ~0.5 allows to discriminate between models and to constrain the range of values of the parameters of each model (Zhang & Meszáros 2002; Schaefer 2003). Also, this relationship shows that the distribution of $E_{p,i}$ is broader than inferred previously basing on the observed E_p values of bright BATSE GRBs. As for the slope of the correlation, the broadness of the $E_{p,i}$ distribution is a crucial test for the prompt emission models (Zhang & Meszáros 2002).

The validity of the $E_{p,i} - E_{iso}$ relationship from the most energetic GRBs to XRFs confirms that these two phenomena have the same origin and is a very challenging observable for jet models. Indeed, these models have to explain not only how E_{iso} and $E_{p,i}$ are linked to the jet opening angle, θ_{jet}, and or to the viewing angle with respect to the jet axis, θ_v, but also how E_{iso} can span over a several orders of magnitudes. In the most simple scenario, the uniform jet model, the observer measures the same value of E_{iso} independently of θ_v. In the other popular scenario, the structured jet model, E_{iso} depends on θ_v. As discussed in previous section, in the hypothesis that achromatic breaks found in the afterglow light curves of GRBs with known redshift are due to collimated emission, it is found that the 'true' radiated energy, E_{jet}, is of the same order for all GRBs and that $E_{iso} \propto \theta_{jet}^{-2}$, assuming a uniform jet. In the case of structured jets, the same observations imply that θ_jet is similar for all GRBs (hence this scenario is also called universal jet model) and $E_{iso} \propto \theta_v^{-2}$. Thus, the found $E_{p,i} - E_{iso}$ relationship implies $E_{p,i} \propto \theta_{jet}^{-1}$ and $E_{p,i} \propto \theta_v^{-1}$ for the uniform and structured jet assumptions, respectively. Lamb, Donaghy & Graziani (2004) argue that the structured universal jet model, in order to explain the validity of the $E_{p,i} - E_{iso}$ relationship from XRFs to energetic GRBs, predicts a number of detected XRFs several orders of magnitude higher than the observed one (∼1/3 than that of GRBs). In their view, the uniform jet model can overcome these problems by assuming a distribution of jet opening angles $N(\theta_{jet}) \propto \theta_{jet}^{-2}$. This implies that the great majority of GRBs have opening angles smaller than $\sim 1°$ and that the true rate of GRBs is several orders of magnitude higher than observed and comparable to that of SN Ic. On the other hand, Zhang et al. (2004) show that the requirement that most GRBs have jet opening angles less than 1 degree, needed in the uniform jet scenario in order to explain the $E_{p,i} - E_{iso}$ relationship, as discussed above, implies values of the fireball kinetic energy and/or of the interstellar medium density much higher than those inferred from the afterglow decay light curves. Together with other authors, e.g. Lloyd–Ronning, Dai & Zhang (2004), they propose a modification of the universal structured jet model, the quasi–universal gaussian structured jet. In this model, the measured E_{iso} undergoes a mild variation for values of θ_v inside a typical angle, which has a quasi–universal value for all GRBs/XRFs, whereas it decreases very rapidly (e.g. exponentially) for values outside the typical angle. In this way, the universal structured jet scenario can reproduce the $E_{p,i} - E_{iso}$ relationship and predict the observed ratio between the number of XRFs and that of GRBs. Also interesting is the off–axis scenario, in which the jet is assumed to be uniform but the measured E_{iso} does not sharply go to zero for $\theta_v > \theta_{jet}$, see e.g. Yamazaki, Ioka & Nakamura (2003). Due to relativistic beaming and Doppler effects, the event is detected by the observer with E_{iso} and $E_{p,i}$ dropping rapidly as θ_v increases. In this models, XRFs are those events seen very off–axis and the XRFs rate with respect to GRBs and the $E_{p,i} - E_{iso}$ relationship can be correctly predicted. In addition to the uniform jet model, the off–axis explanation for very weak and soft events can be applied to the cannon ball (CB) model (Dar 2004).

As we have discussed in previous section and can be seen in Fig. 1, of the two GRBs for which the association with a SN is more firm, one (GRB980425) is characterized by values of $E_{p,i}$ and E_{iso} completely inconsistent with the relationship holding for the other events. From an observational point of view, this is a direct consequence of the fact that the event shows a fluence and a measured peak energy in the range of normal GRBs, while its redshift is much more lower (z = 0.0085). This fact is very challenging for GRB–XRF–SN unification models and for now the most popular explanations assume that the peculiarity of this event is due to particular and uncommon viewing conditions.

Finally, the $E_{p,i}$ and E_{iso} relationship, as for other correlations found for GRBs (e.g. the variability – luminosity correlation), can be used to build a redshift indicator and some attempts have already been done (Atteia 2003).

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